INTRODUCTION TO THE MARS POLAR SCIENCE SPECIAL ISSUE: EXPLORATION PLATFORMS, TECHNOLOGIES AND POTENTIAL FUTURE MISSIONS

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Accepted for publication in the Mars Polar Science special issue of Icarus
December 12, 1999

12 pages
Keywords: Mars, Surface; Mars, Atmosphere; Mars, Climate; Ices; Exobiology

Running head:

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This special issue is the product of the discussions and ideas generated by the more than one hundred terrestrial and planetary scientists who participated in the *First International Conference on Mars Polar Science & Exploration* that was held in Camp Allen, Texas, October 18-22, 1998. The Conference, which was sponsored by the Lunar and Planetary Institute, National Aeronautics and Space Administration, Geological Survey of Canada and the International Glaciological Society, attracted researchers from eleven countries in fields as diverse as glaciology, climatology, planetary geology, planetary atmospheres, geophysics, spacecraft design and instrumentation, remote sensing, and exobiology. The participation of terrestrial scientists proved particularly important, for they contributed an extensive knowledge of Earth analogs, experience with a wide variety of investigative techniques, and a perspective uncolored by the assumptions and interpretations made within the Mars research community over the past 35 years.

The meeting had three main goals: (i) to assess the current state of Mars polar research; (ii) to identify the key questions that motivate our continued exploration of the polar regions; and (iii) to identify the types of investigations that are best suited to address these questions within the next decade. The scientific discussion stimulated by the first pair of these goals is summarized in the topical review by Clifford *et al.* (2000), while the technology and mission aspects associated with the last goal are briefly reviewed here.

With the tragic loss of the recent Mars Polar Lander (MPL) and Deep Space-2 (DS2) missions to the Mars south polar region, it is appropriate to consider the exploration platforms, technologies, and mission concepts that might be employed in the next effort to reach the poles. Equally important, are the enabling technologies and resources associated with telecommunications and power, whose limited availability may significantly constrain the implementation, longevity, and effectiveness of these missions. Finally, we close this review with a brief discussion of two potential missions that were identified by the Conference participants (based on the anticipated success of the MPL and DS2 missions) as having the greatest promise for advancing our understanding of the nature and evolution of the Martian poles.

Exploration Platforms & Technologies.

The principal goal of Mars polar exploration is to determine whether there is an interpretable record of climatic and geologic history preserved within the polar deposits (Clifford *et al.* 2000, Table 1). The answer to this question will require a variety of surface and subsurface observations that will necessitate the development of a broad range of innovative exploration tools and strategies.

Between now and 2007, the potential opportunities for conducting new investigations of the Martian polar regions (beyond those to be carried out by orbital missions already approved for flight) will be limited to a new class of small, low-cost, but technologically-innovative spacecraft called Mars Micromissions. These spacecraft, which are the product of a cooperative effort by NASA and the French space agency, Centre National D'etudes Spatial (CNES), will ride piggyback on commercial launches of the Ariane 5 aboard a carrier spacecraft that can deploy payloads into Mars orbit or to its surface. These missions will be launched on the same schedule as the Mars Surveyor Program launches, or approximately once every 26 months.

Current plans call for the launch of the first pair of Micromissions (one of which will serve as an orbiting telecommunications relay for future missions) in 2003. These will be followed by the launch of an additional pair of Micromissions during each successive Mars opportunity. Open calls for science investigations are anticipated for most of these missions. For 2003, the mass limit for the science payload of a Micromission orbiter is ~5-10 kg. This compares with a maximum payload of ~30-40 kg for a surface or airborne investigation, which includes the mass of the entry system. By 2007, these payload allotments are expected to increase by ~25-50%, due to a more favorable launch opportunity and mass savings in other areas.

Spacecraft trajectory calculations indicate that Micromissions will have the ability to reach the poles during both the 2003 and 2005 launch opportunities, with access to the north easier in 2003 and the south in 2005 (P. Penzo, personal communication). As of this writing, polar Microsmission flight paths for 2007 had yet to be investigated.

Opportunities for later, more ambitious investigations of the polar regions may arise as either follow-ons to the current Mars Surveyor Program, enhanced Micromissions, or missions developed by other nations. Of the various platforms and technologies that might be employed in these investigations, one of the most promising are potential derivatives of the Deep Space-2 microprobe/penetrators (Smrekar and Gavit 1998; Smrekar *et al.* 1999).

The small size and mass (~3.8 kg) of these DS2-class probes makes it possible to deliver multiple payloads to the poles (as well as other locations around the planet) to conduct analyses of the shallow subsurface or to deploy elements of global geophysical or meteorological networks.

Another alternative to traditional lander investigations, is a surface rover. As demonstrated by the Pathfinder mission, rovers provide the ability to access and sample multiple locations – an approach that can be used to characterize the environment surrounding the initial landing site or as part of a long-distance exploratory traverse, spanning up to 1000 km (Stoker 1998a,b). Rover mobility can be accomplished via wheels or tracks, or by legged-walkers. Wheeled rovers can generally traverse over obstacles smaller than half a wheel diameter and can negotiate slopes as great as 45^{o}. In comparison, walkers trade off both ultimate speed and range for the ability to negotiate more complex terrains with steeper slopes.

Aerial platforms offer another type of mobility that bridges the gap in areal coverage and surface resolution between orbital platforms and rovers. Both heavier-than-air (powered aircraft and glider) and lighter-than-air (balloon and aerobot) platforms are practical on Mars. Aircraft offer a more targeted and flexible approach to the investigation of localized surface features than can be achieved by either orbiting spacecraft or higher-flying aerobots. They can also traverse greater distances than all but the most capable rovers. Alternatively, balloons and aerobots (Smith and Cutts 1999) can operate for much longer durations (from days to months), moving more slowly over the terrain and traversing distances of as much as $\sim 10^{4}$ km. Since balloons fly $\sim 10^{2} – 10^{3}$ m above the surface, they are generally unaffected by topographic obstacles. The polar regions are ideal for balloon exploration because the diurnal variations in atmospheric temperature and pressure are small. The north polar region is a particularly attractive site for aerial platforms because of its low elevation and correspondingly greater air mass.

Recent advances in instrument miniaturization allow aerial systems to conduct a broad range of passive and active remote sensing investigations (Smith and Cutts 1999). Indeed, because of their greater proximity to the surface (relative to orbiters), instruments carried by aerial systems can be made smaller and lower power, and yet still achieve high spatial resolution and good signal to noise ratios. Ariel systems can also be used to deploy surface stations and penetrators. This is a role for which balloons are especially well suited because, in addition to the data acquired by these deployments, the instrument packages serve double-duty as expendable ballast.

Of the various experiments that can be conducted or deployed by landers, penetrators, rovers, or aerial systems, seismic and electromagnetic sounding investigations offer the greatest potential for understanding the large-scale internal structure and thermal state of the polar deposits. Slight contrasts in seismic and electrical properties due to differences in composition, density, and volatile state, can be used to construct a three-dimensional picture of the internal stratigraphy, structure, and basal topography of the deposits. These data can be used to detect the presence of basal lakes (and other evidence of basal melting) and can potentially reveal the deformation of internal strata indicative of glacial flow.

Although less practical for conducting general surveys of polar deposit internal structure and properties, targeted drilling investigations offer the opportunity to directly sample the geologic and climatic record preserved at the poles, investigate the compositional, rheologic, and thermophysical properties of the polar ice, search for evidence of life, and validate the interpretations made from local- and regional-scale investigations by geophysical sounders. Current drilling systems can generally be divided into two categories: mechanical systems that penetrate by cutting or shaving ice, and thermal systems that melt through the ice (Kelley *et al.* 1994). In terrestrial applications, mechanical drilling systems have been used to retrieve continuous ice cores over depth intervals of ~10^3 m. Although the mass, energy, and logistical requirements for deep drilling on Mars vastly exceed the capabilities of present and foreseeable robotic missions, drilling to more modest depths (200-400 m) may well be possible with the innovative drilling technologies now in development and the spacecraft power and payload capabilities that may be available in the latter half of this decade.

A viable alternative to recovering ice cores for later analysis is to use a thermal probe to conduct remote, *in-situ* studies of the polar ice at depth (e.g., Philberth 1962; Hansen and Kersten 1984). A thermal probe is an instrumented cylindrical capsule that melts its way through the ice, unwinding a thin cable behind it that is used for power and data transmission between the probe and the support equipment left on the surface. Because the meltwater generated by the probe refreezes behind it, the probe's journey through the ice is a one-way trip. The principal shortcoming of this technique is that any debris present in the melted ice tends to accumulate in front of the probe, slowing and eventually halting its progress, unless sufficient energy is available to melt through the obstruction.

Telecommunications and Power.

To conduct the types of ambitious investigations described above will require significant improvements in both telecommunications and power. The need for major advances telecommunications can be placed in perspective by noting that a single 1024 x 1024 element image, digitized to 12 bits/pixel, results in almost 12.5 mbits of data. Although advanced data compression techniques can reduce this volume by a factor of ~50 or more, current high-resolution multispectral imaging systems are still capable of generating vast amounts of data that must ultimately be either transmitted back to Earth or discarded. Surface rovers and other mobile systems that utilize imaging systems for both science and local navigation, aggravate this problem even further. When this large data volume is combined with the limited bandwidth available to current spacecraft, the restricted opportunities that a polar mission has to transmit data via line-of-sight or by relay through an orbiter as it passes overhead, and the delays imposed by the 4 - 20 minute radio separation between the Earth and Mars, it is no surprise that communication bottlenecks are a serious concern. Over the next seven years, NASA will begin to address this problem by placing a constellation of six small communication/navigation satellites into polar and equatorial orbits around Mars, with the eventual goal of providing a data rate capable of supporting high resolution video. As noted earlier, the first element of this “Mars Network” is scheduled to be launched as a Micromission during the 2003 opportunity.

While there is optimism that telecommunications will become a diminishing constraint on polar mission operations, the same cannot be said for the issue of power. Efficient, reliable power systems are an essential requirement for the exploration of the polar regions, particularly for such energy intensive operations as surface roving and drilling. Currently, the most mature and cost-effective power generation technologies for planetary applications are solar cells and radioisotope thermo-electric generators (RTGs), which utilize the heat generated by the decay of a radioactive material (such as PuO_2) to generate electricity.

For orbiting spacecraft, where the size of solar arrays is not limited by the effects of wind or gravity, solar cells remain the power generation technology of choice. However, for Mars surface applications, especially those at high latitude (where the sun is either below the horizon, or at very low elevations throughout much of the year), reliance on solar cells places serious limits on spacecraft design, capabilities, longevity and operations.

As demonstrated during the Pathfinder mission, solar cells are particularly vulnerable to the accumulation of dust. For this reason, even in the considerably more favorable solar environment that exists at equatorial latitudes, the maximum lifetime of a solar-powered rover is probably less than 90 Martian sols. This lifetime could be extended by the incorporation of some efficient mechanism for dust removal; however, even under these circumstances the operation of a solar powered polar rover would be limited and very unlikely to survive through the winter.

Replacing solar cells with RTGs could vastly improve the lifetime and capabilities of polar rovers, drilling systems, and other surface missions. This potential was demonstrated by Viking Lander 1, which was powered by an RTG and operated on Mars for over six Earth years. A polar rover equipped with a similar power source could potentially traverse the entire north polar cap in a comparable period of time.

Aside from their significant advantages in power output and longevity, RTGs have several other characteristics that make them desirable for polar applications: they are relatively compact, inherently reliable, and the waste heat they produce can be used to keep equipment and instruments warmed to optimal operational temperatures. Their principal disadvantages of RTGs are their comparatively high cost and public concerns regarding their safety.

Although RTGs were used on the Viking Landers, and are currently employed on the Galileo and Cassini spacecraft, they are presently excluded from the Mars Surveyor Program – with no indication as to whether this internal policy will be reversed for future missions. Although alternative power generation technologies (like fuel cells) exist, their sustained use at the power levels attainable by RTGs requires frequent refueling. While this capability may eventually be possible with *in situ* resource utilization, the mass and complexity of the required infrastructure appears to seriously limit or preclude the use of fuel cells for many low-mass polar missions.

High Priority Missions.

Based on consideration of the key questions and needed observations identified during the *First International Conference on Mars Polar Science and Exploration* (Clifford *et al*. 2000, Table 1), a variety of potential missions were discussed in an effort to identify those which offered the potential for the greatest scientific return in a spacecraft whose costs and technical requirements were sufficiently modest that it could conceivably be flown within the next decade. During that discussion, two missions were widely acknowledged as satisfying these goals: (i) a rover traverse down the exposed stratigraphy of a north polar cap trough wall, and (ii) a meteorology network mission.

The rationale for a traverse down the layered stratigraphy of a trough wall is that it provides an opportunity to directly sample the geologic and climatic history preserved in the polar ice at a fraction of the cost of a more traditional ice core drilling effort. This strategy was first proposed by Fisher (1993) based on the original terrestrial implementation by Reeh *et al.* (1991) who, by conducting a 700 m cross-strata traverse at the margin of the Greenland ice sheet, were able to sample a continuous record of over 10^5 years of Earth's climate history. By equipping a Mars polar rover with a small (1-3 m) ice-coring drill, and by drilling at small enough intervals during the descent down a trough wall to insure overlap between successive vertical cores, it should be possible to sample and analyze a similar continuos record of Martian polar stratigraphy extending as much as a kilometer deep. This strategy provides a way of conducting *in situ* measurements of stratigraphic variations in the relative abundance of ice and dust; the thickness and scale of individual layers; the thermophysical, rheologic, and petrologic properties of the polar ice; as well as the potential presence of other contaminants (such as volcanic ash, salts, atmospheric isotopes, micrometeorites, and possible biomarkers of indigenous life) in a single, comparatively low-cost mission. Possible enhancements to this approach include the potential for caching selected cores (or parts of cores) for sample return to Earth, and the possibility of applying *in-situ* dating techniques, such as thermal luminescence (Lepper and McKeever 2000), that would be of enormous assistance in interpreting the stratigraphic record.

Although not as readily identifiable a "polar" mission as the trough wall traverse, the second high priority mission identified by the Conference participants was the deployment of a long-duration multi-element meteorology network. Such a mission is critical because, to understand the nature of past climates, we must first understand the nature of the present. The key to this understanding is the general circulation of the Martian atmosphere, which determines the planet's climate system through its control of the coupled seasonal cycles of carbon dioxide, water and dust. However, this knowledge can only be obtained by a significant increase in the resolution, frequency, and duration of local and global atmospheric monitoring.

A meteorological network mission can help define the general circulation of the Martian atmosphere through long-term observations of the meteorological regimes in the tropics, midlatitudes, and polar regions of both hemispheres. The minimum characterization necessary to satisfy this need is a high-resolution temporal record of atmospheric pressure and optical depth at 16 globally-distributed stations over several Mars years (Haberle and Catling 1996). Fortunately, stations accommodating this limited payload can be designed small and light enough that they can be flown on a single flight of a Med-lite launch vehicle or deployed incrementally over several Micromission opportunities.

Summary.

NASA’s Mars Surveyor Program has already begun to address many key questions about the nature and evolution of the Martian polar regions -- an effort that will soon be enhanced by the complementary investigations of the European Space Agency’s 2003 Mars Express mission. However, answers to some of the most important questions will require a variety of more ambitious *in situ* investigations, ranging from the analysis and dating of the Martian polar stratigraphy, to the establishment of a global network of meteorological stations to understand the factors that have influenced the planet’s past and present climate.

This effort will require the knowledge, skills, and cooperation of researchers from a wide range of fields. Most importantly, it will require the participation of terrestrial scientists whose expertise and knowledge of Earth analogs represents an invaluable resource for the interpretation of incoming data and for stimulating new experiments and ideas for future missions to the Martian poles. It is hoped that the *Second International Conference on Mars Polar Science & Exploration*, that will be held in Reykjavick, Iceland, August 21-25, 2000 (http://www.lpi.usra.edu/meetings/polar2000/), will continue to promote these cooperative and interdisciplinary efforts and provide an opportunity for terrestrial and planetary scientists to discuss the many new and exciting discoveries that the Mars Global Surveyor spacecraft has made about the Martian polar regions since the *First Conference* in October 1998.

Acknowledgements: The authors would like to express their gratitude to Eric Blake, Wendy Calvin, Jonathan Cameron, David Crisp, Jim Cutts, Bob Haberle, Alan Howard, Paul Penzo, Stephen Platt, Susan Smrekar, Carol Stoker, and Richard Zurek, who contributed to various portions of this discussion.

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Conveners

First International Conference on Mars Polar Science & Exploration

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